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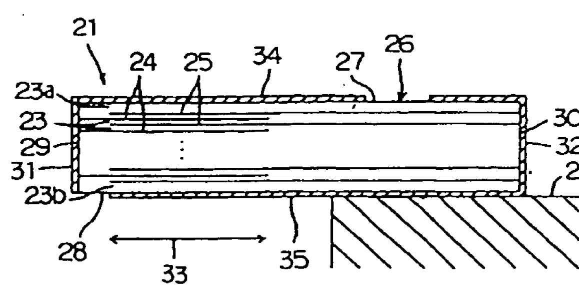
(54) **Piezoelectric actuator**

(57) A piezoelectric actuator in which of the piezoelectric layers 23a and 23b, being the outermost layers of an actuator body 26 with a layered structure onto which are formed an outer electrode 31 and an outer electrode 32 on both end surfaces 29 and 30, the piezoelectric layer 23a is made piezoelectrically active as a result of making an extension portion 34 of the first outer electrode 31, through the piezoelectric layer 23a, face inner electrodes 25 with a polarity which is different from that of the extension portion 34, while the piezoelectric layer 23b is made piezoelectrically inactive as a result of either making an extension portion 35 of a second outer electrode 32 face, through the piezoelectric layer 23b, the inner electrodes 25 with a polarity which is identical to that of the extension portion 35 of the second outer electrode 32 or as a result of not forming an extension portion on the outer electrode. This causes the displacement value caused by bending to be added to the usual d_{31} component displacement, thereby increasing the amount of displacement as a whole.

[FIG. 1]



EP 0 901 172 A1

Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to a piezoelectric actuator, and, more particularly, to an improvement in a d_{31} type layered piezoelectric actuator which undergoes a large displacement.

2. Description of the Related Art

[0002] A conventional d_{31} type layered piezoelectric actuator 1, which is considered as an interesting conventional actuator in the present invention, is shown in Fig. 8. The d_{31} type layered piezoelectric actuator 1 is planar and substantially rectangular in a longitudinal direction, with one side of the actuator 1, in the longitudinal direction, being fixed to a fixing portion 2, such as a base, and with the end at the other side undergoing displacement.

[0003] The piezoelectric actuator 1 has an actuator body 6 with a layered structure of a plurality of piezoelectric layers 3 and a plurality of inner electrodes 4 and 5 that are formed between the piezoelectric layers 3. The actuator body 6 has a first major surface 7 and a second major surface 8, as well as a first end surface 9 and a second end surface 10, with the major surfaces 7 and 8 formed by the outwardly facing major surfaces of the two piezoelectric layers 3a and 3b that form the outermost layers and with the end surfaces 9 and 10 formed by the end surfaces of the plurality of piezoelectric layers 3.

[0004] On the first end surface 9 and the second end surface 10 of the actuator body 6 are formed a first outer electrode 11 and a second outer electrode 11, respectively. In order to actuate the piezoelectric actuator, a voltage is applied to the first and the second outer electrodes 11 and 12 from outside the actuator body 6.

[0005] The aforementioned inner electrodes 4 are called first inner electrodes 4 which are connected to the first outer electrode 11 on the first end surface 9, while the inner electrodes 5 are called second inner electrodes 5 which are connected to the second outer electrode 12 on the second end surface 10. Applying a voltage to the outer electrodes 11 and 12 causes the first inner electrodes 4 and the second inner electrodes 5 to have different polarities. The first inner electrodes 4 and the second inner electrodes 5 are alternately disposed in the direction in which they are placed upon each other.

[0006] At the first end surface 9 side of the actuator body 6 is formed a piezoelectrically active area 13 which is formed by placing the first inner electrodes 4 and the second inner electrodes 5 upon each other. The piezoelectrically active area 13 is formed closer to one end of the actuator than the portion of the actuator fixed to the fixing portion 2. At the second end surface 10 side of the actuator body 6 is formed a piezoelectrically inactive area which corresponds to the fixing area to be fixed to the fixing portion 2. The fixing area is fixed so that the piezoelectric actuator 1 does not peel off from the fixing portion 2 when the actuator body 6 is undergoing displacement.

[0007] For the purpose of increasing displacement, the piezoelectric layers 3a and 3b, being the outmost layers, of the illustrated piezoelectric actuator 1 are formed so as to be piezoelectrically active within at least the piezoelectric active area 13. More specifically, the first outer electrode 11 has an extension portion 14 and an extension portion 15 which extend to the first major surface 7 and the second major surface 8, respectively, with the extension portion 14 facing, through the piezoelectric layer 3a at the first major surface 7 side, the second inner electrodes 5 having a polarity which is different from that of the first outer electrode 11, and the extension portion 15 facing, through the piezoelectric layer 3b at the second major surface 8 side, the second inner electrodes 15.

[0008] A form of displacement of the piezoelectric actuator 1 is shown in Fig. 9. In Fig. 9, the piezoelectric actuator 1 gets deformed to the shape indicated by broken lines, causing displacement 16 of one end portion of the piezoelectric actuator 1 as indicated by the arrow.

[0009] The above-described piezoelectric actuator, though displaced by only a small amount, is displaced easily and quickly, so that it can be advantageously used, in practice, in inkjet printers. However, when a high-performance printer is to be realized, it is necessary to discharge ink in large amounts. In such a case, an actuator which can undergo a large displacement is desired.

[0010] To achieve this, progress has been made in the development of a new material with a large d_{31} constant and a highly efficient d_{31} type actuator, but not to the point where the piezoelectric actuator which has sufficient performance can be produced. For the development of a new material, in particular, considerable effort and time are required to increase the d_{31} constant by only a few percent.

SUMMARY OF THE INVENTION

[0011] Accordingly, it is an object of the present invention to provide a piezoelectric actuator which can relatively easily be displaced by a larger amount, without relying on the development of a new material.

[0012] The preferred embodiment of the present invention provides a d_{31} type layered piezoelectric actuator which includes an actuator body with a layered structure of a plurality of piezoelectric layers and a plurality of inner electrodes formed between the piezoelectric layers. The actuator body has a first major surface and a second major surface, as well as a first end surface and a second end surface, with the first and the

second major surfaces being formed by outwardly facing major surfaces of the two piezoelectric layers being the outermost layers, and with the first and the second end surfaces being formed by the end surfaces of the piezoelectric layers. The piezoelectric actuator also includes a first outer electrode and a second outer electrode, which are formed on at least the first end surface and the second end surface of the actuator body. The inner electrodes are classified either as a first inner electrode which is connected to the first outer electrode on the first end surface or as a second inner electrode which is connected to the second outer electrode on the second end surface. The first inner electrodes and the second inner electrodes are alternately disposed in a direction in which they are placed upon each other. The actuator body has a piezoelectrically active area formed by placing the first inner electrodes and the second inner electrodes upon each other. The first outer electrode has an extension portion which extends to the first major surface of the actuator body. In the piezoelectrically active area, the second inner electrodes face, through the piezoelectric layer that is the outermost layer at the first major surface side, the extension portion of the first outer electrode, whereby the piezoelectric layer that is the outmost layer at the first major surface side becomes piezoelectrically active, so that a large displacement occurs. The piezoelectric layer that is the outermost layer at the second major surface side is piezoelectrically inactive.

[0013] Therefore, the displacement value caused by bending is added to the d_{31} component displacement, making it possible to increase the efficiency with which the displacement occurs and to increase the displacement as a whole.

[0014] Accordingly, when the piezoelectric actuator of the-present invention is applied, for example, to an inkjet printer, a larger amount of ink can be discharged, resulting in improved printer performance.

[0015] In the above described piezoelectric actuator, when either one of the first outer electrode and the second outer electrode has an extension portion which extends to the second major surface, the piezoelectric layer that is the outermost layer at the second major surface side is made piezoelectrically inactive. Therefore, when, at the piezoelectrically active area, the inner electrodes, with the same polarity as the outer electrode having the extension portion which extends to the second major surface, faces the extension portion which extends to the second major surface, the piezoelectric layer which is the outermost layer at the second major surface side can be reliably made piezoelectrically inactive, since the inner electrodes and the facing extension portion of the outer electrode have the same polarity.

[0016] In addition, when the first and second outer electrodes are essentially not formed on the second major surface, in the piezoelectrically active area, causing the piezoelectric layer which is the outmost layer at the second major surface side to become piezoelectrically inactive, the piezoelectric layer, which is the outermost layer at the second major surface side, is reliably made piezoelectrically inactive, regardless of the polarity of the inner electrodes formed inwardly along the piezoelectric layer which is the outermost layer at the second major surface side.

[0017] Further, when the actuator body is formed such that it has a piezoelectrically active area at one end in a longitudinal direction thereof and a piezoelectrically inactive area at the other end in the longitudinal direction thereof, with the piezoelectrically inactive area being a fixing area to be fixed to a fixing portion, it is possible to prevent the piezoelectric actuator from separating from the fixing portion when the actuator body is undergoing displacement. Separation from the fixing portion tends to occur in piezoelectric actuators, such as the piezoelectric actuator of the present invention, whose displacement is made larger as a whole as a result of being bent. Therefore, forming the actuator body in such a manner is particularly effective in preventing separation from the fixing portion in such piezoelectric actuators.

[0018] Other features and advantages of the present invention will become apparent from the following description of the invention which refers to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019]

Fig. 1 is a cross sectional view of a d_{31} type layered piezoelectric actuator 21 being mounted to a fixing portion 22, in a preferred embodiment of the present invention.

Fig. 2 is a front view illustrating a form of displacement of the piezoelectric actuator 21 of Fig. 1.

Fig. 3 is a view showing a form of displacement of a conventional piezoelectric actuator 1 shown in Fig. 8, based on FEM simulation.

Fig. 4 is a graph showing the distribution of the amount of displacement of one end of the piezoelectric actuator 1 in the X direction and in the Z direction, based on the results of the FEM simulation illustrated in Fig. 3.

Fig. 5 is a view showing a form of displacement of the piezoelectric actuator 21 shown in Fig. 1, based on FEM simulation.

Fig. 6 is a graph showing the distribution of the amount of displacement of one end of the piezoelectric actuator 21 in the X direction and in the Z direction, based on the results of the FEM simulation illustrated in Fig. 5.

Fig. 7, which corresponds to Fig. 1, is a view showing a d_{31} type layered piezoelectric actuator 41, in another embodiment in accordance with the present invention.

Fig. 8, which corresponds to Fig. 1, is a view show-

ing a conventional d_{31} type piezoelectric actuator 1 which is considered as an interesting conventional actuator in the present invention.

Fig. 9, which corresponds to Fig. 2, is a view showing a form of displacement of the piezoelectric actuator 1 of Fig. 8.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] Fig. 1, which corresponds to Fig. 8, is a view showing a d_{31} type layered piezoelectric actuator 21 in an embodiment in accordance with the present invention.

[0021] As described below, the piezoelectric actuator 21 and the piezoelectric 1 of Fig. 8 share many common features.

[0022] The piezoelectric actuator 21 is planar and substantially rectangular in a longitudinal direction, with one side of the piezoelectric actuator 21, in the longitudinal direction thereof, being fixed to a fixing portion 22, such as a base, and the end at the other side of the piezoelectric actuator 21 undergoing displacement.

[0023] The piezoelectric actuator 21 has an actuator body with a layered structure of a plurality of piezoelectric layers 23 and a plurality of inner electrodes 24 and 25 that are formed between the piezoelectric layers 23. Each piezoelectric layer 23 is made of a piezoelectric ceramic material such as a PZT type ceramic material (lead titanate zirconate), and each of the inner electrodes 24 and 25 is made of, for example, Ag/Pd. One piezoelectric layer 23 is, for example, 20 μm thick, whereas one inner electrode 24 and one inner electrode 25 are, for example, 2 μm thick.

[0024] The actuator body 26 is usually formed, by an integral baking process, into one having a first major surface 27 and a second major surface 28, as well as a first end surface 29 and a second end surface 30, with the first and second major surfaces 27 and 28, respectively, being formed by the outwardly facing major surfaces of two piezoelectric layers 23a and 23b that form the outmost layers of the actuator body 26, and with the first and second end surfaces 29 and 30 being formed by the end surfaces of the plurality of piezoelectric layers 23.

[0025] On the first end surface 29 and the second end surface 30 of the actuator body 26 are formed a first outer electrode 31 and a second outer electrode 32, respectively. The outer electrodes 31 and 32 are composed of a plurality of thin film electrode sections made of Cr, Au, or the like. In order to actuate the piezoelectric actuator 21, a voltage is applied to the first and the second outer electrodes 31 and 32 from outside the actuator body 26.

[0026] The inner electrodes 24 are called first inner electrodes 24 that are connected to the first outer electrode 31 on the first end surface 29, while the inner electrodes 25 are called second inner electrodes 25 which are connected to the second outer electrode 32 on the second end surface 30. Therefore, applying a voltage to the outer electrodes 31 and 32 causes the first inner electrodes 24 and the second inner electrodes 25 to have different polarities. The first inner electrodes 24 and the second inner electrodes 25 are alternately disposed in a direction in which they are placed upon each other.

[0027] At the first end surface 29 side of the actuator body 26 is formed a piezoelectrically active area 33 which is formed by placing the first inner electrodes 24 and the second inner electrodes 25 upon each other. At the second end surface 30 side of the actuator body 26 is formed a piezoelectrically inactive area which corresponds to the fixing area to be fixed to the fixing portion 22. The fixing area is fixed so that the actuator body 26 does not peel off from the fixing portion 22 when the actuator body 26 is undergoing displacement.

[0028] At the piezoelectrically active area 33, the first outer electrode 31 has an extension portion 34 which extends to the first major surface 27 and faces, through the piezoelectric layer 23a which is the outmost layer at the first major surface 27 side, the second inner electrodes 25. The second inner electrodes 25 have a polarity different from that of the first outer electrode 31, so that the piezoelectric layer 32a is piezoelectrically active.

[0029] Accordingly, the above-described piezoelectric actuator 21 and the piezoelectric actuator 1 of Fig. 8 share common features.

[0030] In the present embodiment, the first outer electrode 31 does not extend to the second major surface 28, whereas the second outer electrode 32 has, at the piezoelectrically inactive area 33, an extension portion 35 that extends to the second surface 28. The extension portion 35 faces the second inner electrodes 25 through the piezoelectric layer 23b which is the outmost layer at the second major surface 28 side. Since the second inner electrodes 25 have the same polarity as the second outer electrode 32, the piezoelectric layer 23b is piezoelectrically inactive.

[0031] Fig. 2, which corresponds to Fig. 9, illustrates a form of displacement of the piezoelectric actuator 21. As indicated by the broken lines of Fig. 2, the piezoelectric actuator 21 bends when it is being deformed, causing a displacement 36 of an end portion of the piezoelectric actuator 21, as shown by the arrow. Such bending of the piezoelectric actuator 21 occurs when the piezoelectric layer 23b, which becomes piezoelectrically inactive, does not deform piezoelectrically. Accordingly, in the piezoelectric actuator 21, when displacement caused by bending is added to the d_{31} component displacement, the overall displacement 36 occurs more efficiently and is greater than the usual d_{31} component displacement 16 illustrated in Fig. 9, so a large displacement occurs.

[0032] Although in the embodiment shown in Fig. 1 the second outer electrode 32 was the electrode having

extension portion 35 that extends to the second major surface 28, in other embodiments the first outer electrode 31 may be the electrode having the extension portion that extends to the second major surface 28. In this case, selection of the arrangement of the inner electrodes 24 and 25 may be made such that the first inner electrodes 24, having the same polarity as the first outer electrode 31, faces, through the piezoelectric layer 23b which is the outmost layer at the second major surface 28 side, the extension portion of the first outer electrode 31.

[0033] Based on the displacement simulation results of the piezoelectric actuator 21 using the finite element method (FEM), a comparison is made between the embodiment of the piezoelectric actuator 21 of Fig. 1 in accordance with the present invention and the conventional piezoelectric actuator 1 of Fig. 8.

[0034] Fig. 3 is a view showing a form of displacement occurring in the conventional piezoelectric actuator 1, based on FEM simulation results, while Fig. 4 is a graph showing the distribution in the amount of displacement of one end portion of the piezoelectric actuator 1 in the X direction and in the Z direction, when a voltage, with a frequency of 1.000000 x 10^3 Hz, is been applied to the outer electrodes 11 and 12. It is to be noted that the X direction and the Z direction are indicated in Fig. 3. The fixing area 17 to be fixed to the fixing portion 2 is also shown in Fig. 3.

[0035] In the FEM simulation, the overall length of the piezoelectric actuator 1 is 7 mm, the length of the piezoelectric active area 33 is 2.5 mm, the length and the thickness of the fixing area 17 are 4 mm and 0.72 mm, respectively.

[0036] As shown in Fig. 3, one end portion of the conventional piezoelectric actuator 1 essentially deforms only in the X direction, with the maximum displacement of the one end portion thereof being 0.76 μm, as shown in Fig. 4.

[0037] Figs. 5, which corresponds to Fig. 3, is a view showing a form of displacement occuring in the piezoelectric actuator 21 of the embodiment, whereas Fig. 6, which corresponds to Fig. 4, is a graph showing the amount of displacement of one end portion of the piezoelectric actuator 21 in the X direction. It is to be noted that Fig. 5 shows the fixing area 37 to be fixed to the fixing portion 22.

[0038] As shown in Fig. 5, one end portion of the piezoelectric actuator 21 of the present embodiment deforms not only in the X direction, but also in the Z direction, with the maximum amount of displacement of the one end portion in the X direction being 0.82 μm as shown in Fig. 6, which is 8% larger than the conventional maximum displacement amount shown in Fig. 4. Since the overall bending effect in increasing the efficiency with which displacement occurs is greater than the effect in reducing this efficiency, caused by the piezoelectric layer 23b becoming piezoelectrically inactive, the amount of displacement is increased.

[0039] For example, in the case where the piezoelectric actuator 21 of the present embodiment is applied to an inkjet printer, when the bending becomes too large, causing a large amount of displacement in the Z direction, the direction in which ink is discharged tends to vary. Therefore, for specific applications, it is necessary to consider the amount of bending.

[0040] Fig. 7, which corresponds to Fig. 1, is a view showing a piezoelectric actuator 41 in another embodiment of the present invention. In Fig. 7, corresponding parts to those of Fig. 1 are given the same reference numerals. Descriptions which overlap are not given below.

[0041] In the embodiment illustrated in Fig. 7, both the first outer electrode 31 and the second outer electrode 32 are not essentially formed on a second major surface 28, at a piezoelectric active area 33, causing a piezoelectric layer 23b at the second major surface 28 side to be piezoelectrically inactive.

[0042] In Fig. 7, although a space, which is the same size as the thickness of the second outer electrode 32, is formed between an actuator body 26 and a fixing portion 22, such a space is actually filled with an adhesive used for fixing the piezoelectric actuator 41 to the fixing portion 22.

[0043] Similarly with the piezoelectric actuator 21 of Fig. 1, it has been confirmed that the piezoelectric actuator 41 of the present embodiment undergoes displacements such as those shown in Figs. 2 and 5, and has the displacement values and the displacement amount distribution shown in Fig. 6.

[0044] Although in Fig. 7 the inner electrodes that are placed directly above the piezoelectric layer 23b at the second major surface 28 side are the second inner electrodes 25 that have the same polarity as the second outer electrode 32, the first inner electrodes 24 that have the same polarity as the first outer electrode 31 may be placed directly thereabove instead of the second inner electrodes 25.

[0045] In the structure of Fig. 7, the first outer electrode 31 has an extension portion 42 which extends to the second major surface 28, with one end portion of the extension portion 42 being located slightly within the piezoelectrically active area 33, so that one end portion of the extension portion 42, through the piezoelectric layer 23b, faces only a very small portion of the second inner electrodes which have a polarity different from that of the extension portion 42. Making one end portion of the extension portion 42 face only a very small portion of the second inner electrodes is not sufficient to make the piezoelectric layer 23b piezoelectrically active. Accordingly, it is to be understood that an embodiment in which either the first outer electrode 31 or the second outer electrode 32 is formed along only a very small portion of the second major surface 28 falls within the scope of the present invention.

[0046] While the invention has been particularly shown and described with reference to preferred

embodiments thereof, it will be understood by those skilled man in the art that the forgoing and other changes in form and details may be made therein without departing from the spirit of the invention.

Claims

1. A d_{31} type piezoelectric actuator, comprising:

   an actuator body including a laminated structure of a plurality of piezoelectric layers and a plurality of inner electrodes formed between said piezoelectric layers;
   said actuator body having a first major surface, a second major surface, a first end surface and a second end surface;
   said first major surface and said second major surface being provided by outwardly facing major surfaces of two of the plurality of piezoelectric layers being the outermost layers;
   said first end surface and said second end surface being provided by the end surfaces of said piezoelectric layers; and
   a first outer electrode and a second outer electrode, which are provided on at least said first end surface and said second end surface, respectively, for applying thereto a voltage from the outside;
   said inner electrodes being classified either as a first inner electrode connected to said first outer electrode at said first end surface or as a second inner electrode connected to said second outer electrode at said second end surface;
   said first inner electrodes and said second inner electrodes being alternately disposed in a direction in which said first and said second inner electrodes are laminated to each other;
   said actuator body having a piezoelectrically active area provided by placing said first inner electrodes and said second inner electrodes upon each other;
   said first outer electrode having an extension portion which extends to said first major surface; and
   said second inner electrodes facing said extension portion of said first outer electrode in said peizoelectrically active area through said piezoelectric layer which is the outermost layer at said first major surface side, whereby said piezoelectric layer, which is the outermost layer at said first major surface side, becomes piezoelectrically active, and said piezoelectric layer, which is the outmost layer at said second major surface side, becomes piezoelectrically inactive.

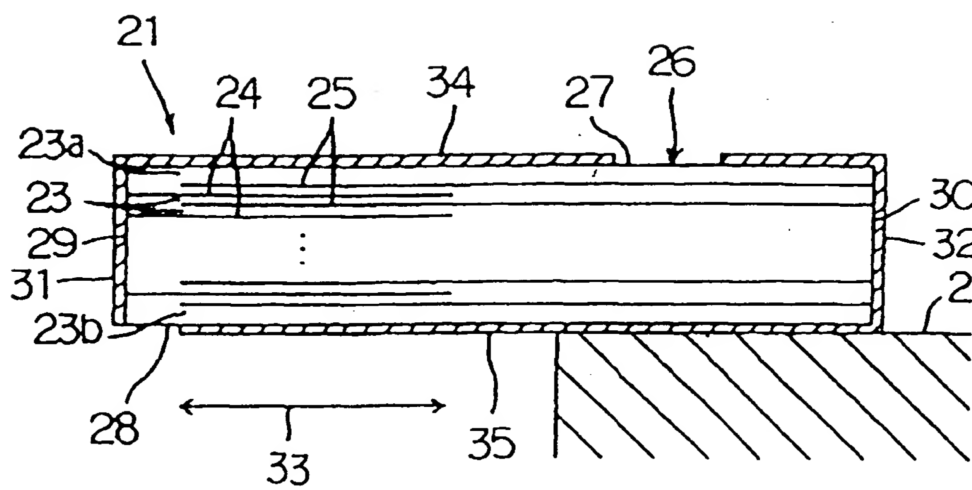
2. The piezoelectric actuator according to Claim 1, wherein either one of said first outer electrode and said second outer electrode has an extension portion which extends to said second major surface; and

   said inner electrodes, having the same polarity as said outer electrode having said extension portion which extends to said second major surface, faces said extension portion which extends to said second major surface in said piezoelectric active area through said piezoelectric layer being the outmost layer at said second major surface side, whereby said piezoelectric layer, being the outmost layer at said second major surface side, becomes piezoelectrically inactive.

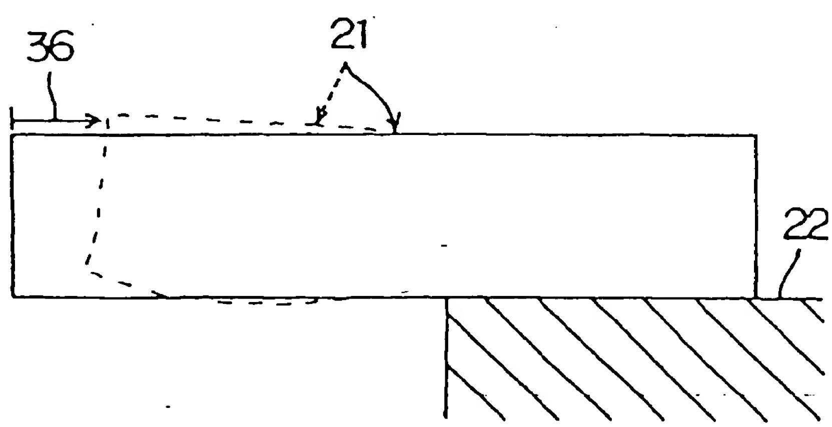
3. The piezoelectric actuator according to Claim 1, wherein both of said first and second outer electrodes are essentially not provided on said second major surface, in said piezoelectrically active area, whereby said piezoelectric layer, which is the outermost layer at said second major surface side, becomes piezoelectrically inactive.

4. The piezoelectric actuator according to any one of Claims 1 to 3, wherein said actuator body has said piezoelectrically active area at one side in a longitudinal direction thereof, and a piezoelectrically inactive area at the other side in the longitudinal direction thereof, said piezoelectrically inactive area being a fixing area to be fixed to a fixing portion.

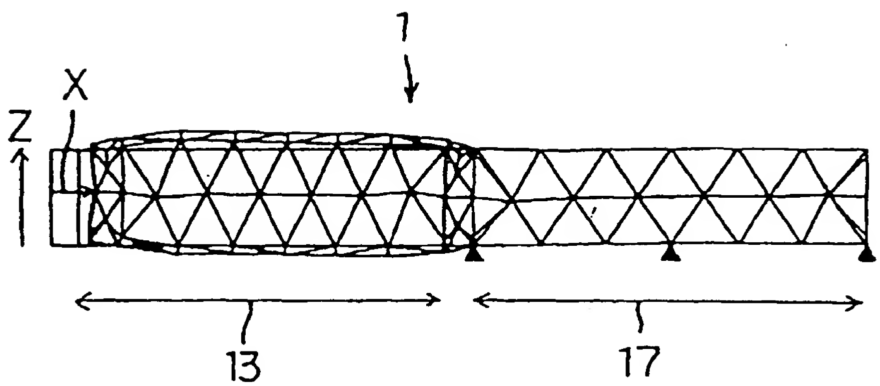
[FIG. 1]



[FIG. 2]



[FIG. 3]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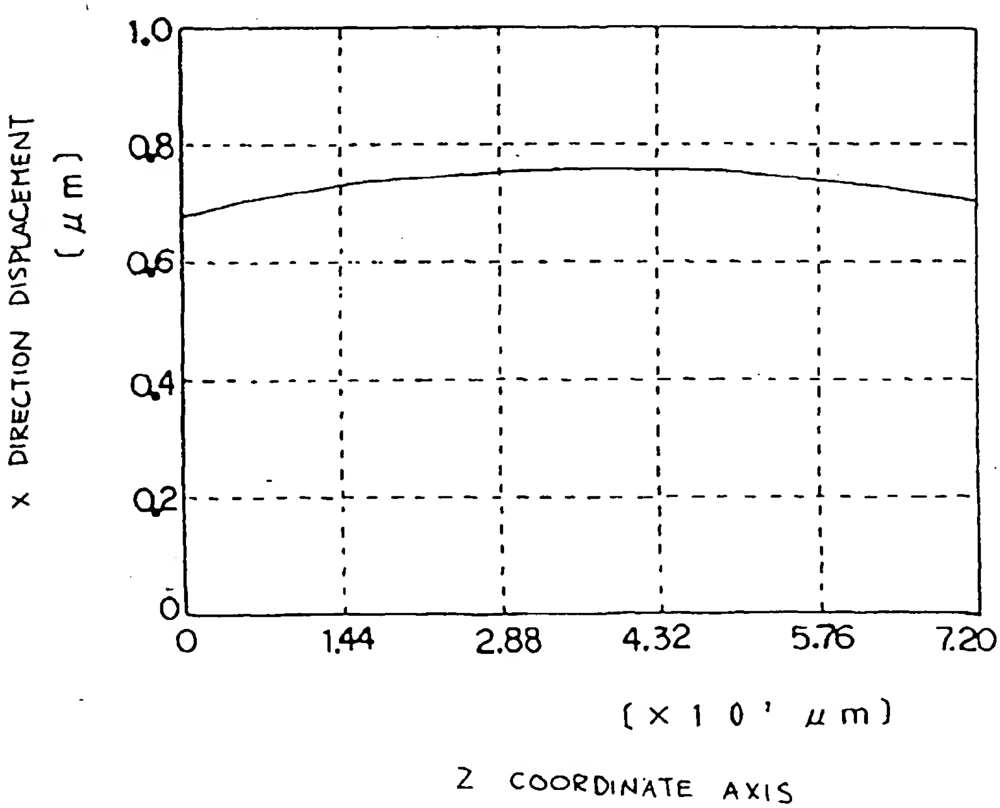
[FIG. 4]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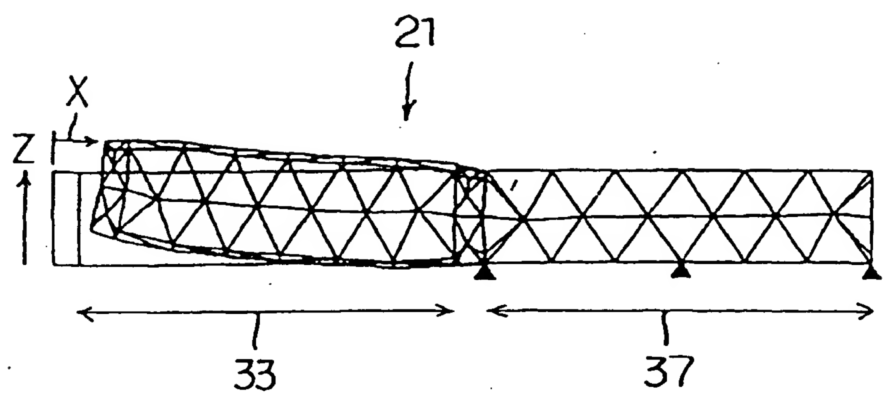
Z COORDINATE AXIS

[FIG. 5]


21
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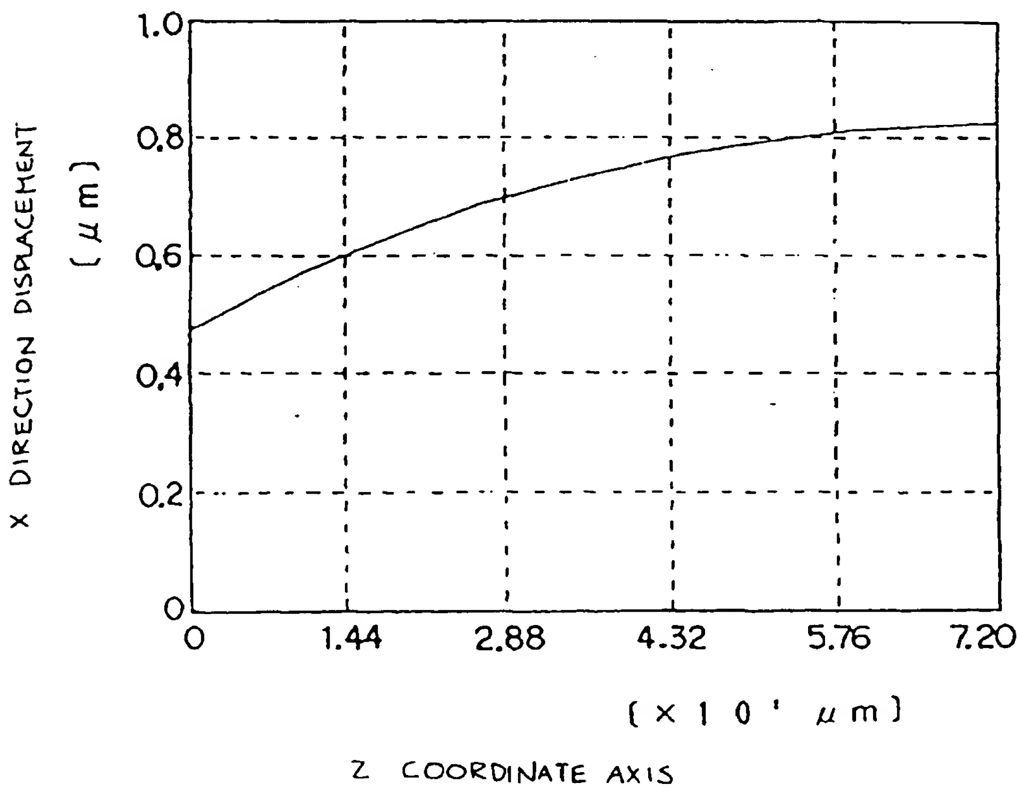
33
37

[FIG. 6]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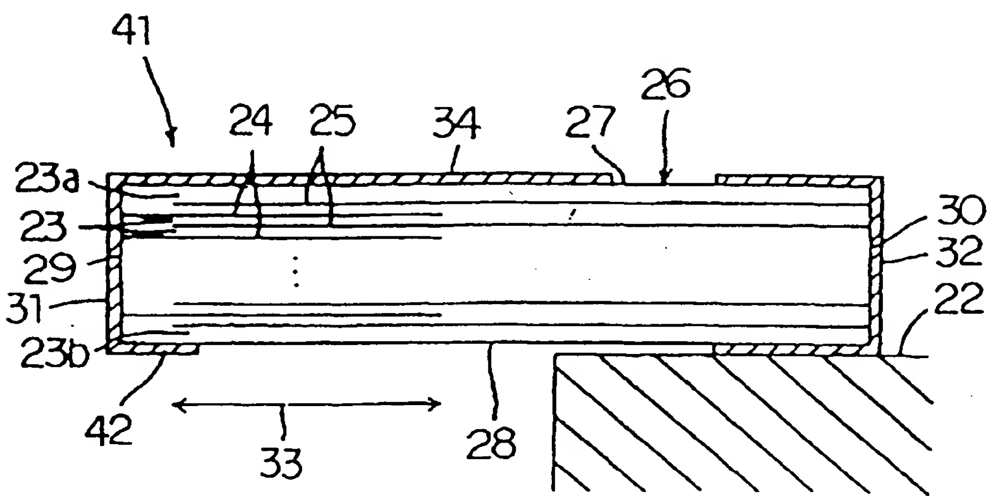
[FIG. 7]


41
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23a
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23b
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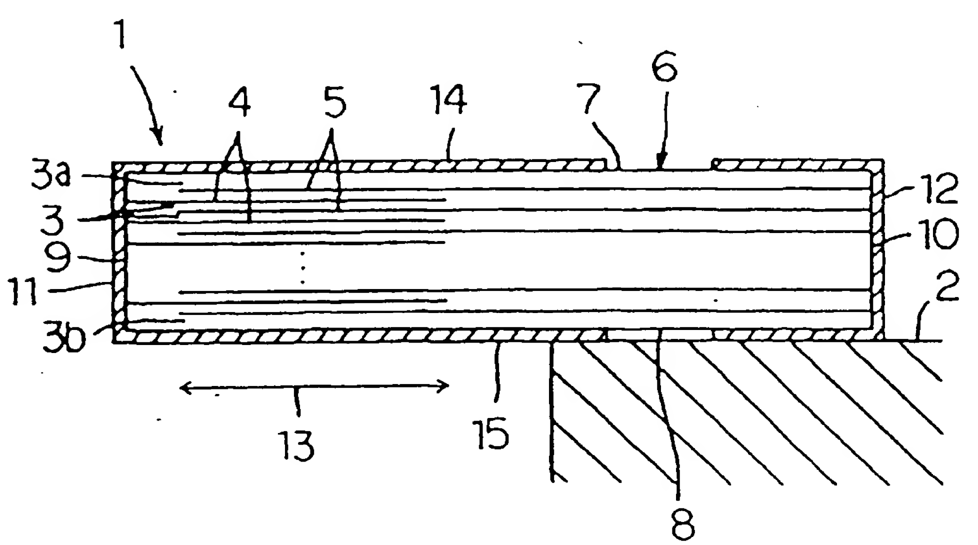
[FIG. 8]


1
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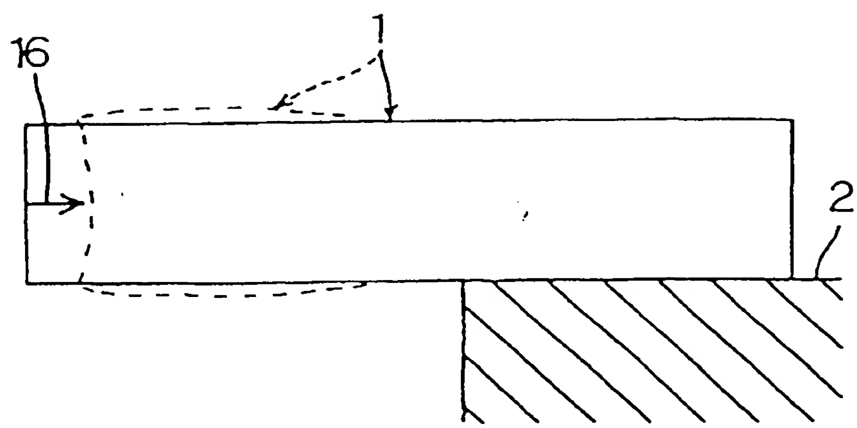
[FIG. 9]



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EUROPEAN SEARCH REPORT

Application Number
EP 98 11 6210

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	EP 0 703 078 A (SEIKO EPSON CORP) 27 March 1996 * column 4, line 20-31; figures 3A,3B *	1	H01L41/083
A	PATENT ABSTRACTS OF JAPAN vol. 095, no. 010, 30 November 1995 & JP 07 178902 A (SEIKO EPSON CORP), 18 July 1995 * abstract *	1	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			H01L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	27 November 1998	Pelsers, L

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27-11-1998

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0703078 A	27-03-1996	JP 8150716 A	11-06-1996
		US 5784085 A	21-07-1998

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82